View metadata, citation and similar papers at core.ac.uk

brought to you by CORE

provided by Elsevier - Publisher Connector

ELSEVIER

Available online at www.sciencedirect.com

ScienceDirect

Procedia Engineering 5 (2010) 1127–1130

Procedia Engineering

www.elsevier.com/locate/procedia

Proc. Eurosensors XXIV, September 5-8, 2010, Linz, Austria

Ultrasensitive nanowire pressure sensor makes its debut

Bo Woon Soon[1,ζ], Pavel Neuzil[1,δ], Chee Chung Wong[1,2], Julien Reboud[1], Han Hua Feng[1], Chengkuo Lee[3,*]

[1]*Institute of Microelectronics (IME), A*STAR (Agency for Science, Technolog and Research), Singapore*
[2]*Division of Bioengineering, Nanyang technological University, Singapore*
[3]*Department of Electrical and Computer Engineering, National University of Singapore, Singapore*

Abstract

A membrane pressure sensor with embedded piezoresistive silicon nanowires (NW) has been demonstrated to have an ultrasensitive piezoresistive response of $(\Delta R/R)/\Delta P$ of 13 Pa^{-1}. This was achieved through the effective tuning of the transverse electric field across the NW. The fabrication of the sensor is fully based on CMOS compatible technique. *P*-type ⟨110⟩ oriented NWs with a square cross-section of 100 nm were fabricated on silicon-on-insulator (SOI) wafers, acting as the sensing elements. The NWs' exceptional properties and minute size will enable further shrinking of footprint of pressure sensors and other NEMS sensors with increased sensitivity, opening a way to new applications like implantable medical devices.

© 2010 Published by Elsevier Ltd. Open access under CC BY-NC-ND license.

Keywords: Silicon nanowire; Giant piezoresistivity; Pressure sensor; NEMS

1. Introduction

The effort of scaling down diverse devices such as microelectromechanical systems (MEMS) to nanoelectromechanical systems (NEMS) has triggered a rapid development in micromachining technology, and has created a range of novel nanomaterials, e.g. semiconductor nanowires (NW), single walled carbon nanotubes (SWNT) and carbon graphene. Semiconductor NWs, particularly silicon-based ones, have enormous potential as the next most promising material in nanoscale devices because of their scalability, established material database and above all, mature fabrication process. The research in NWs has recently confirmed their usability in various device applications from numerous fields, such as nanomechanical devices [1] and electromechanical sensors [2]. We found that the NW is an astounding material with exceptional characteristics for different applications. He et al. have reported the giant piezoresistance phenomenon in *p*-type silicon NWs that yields a piezoresistivity with almost two orders of magnitude larger than that of bulk silicon [3]. Silicon NW has reasonably high Young's Modulus of

[ζ]*E-mail: soonbw@ime.a-star.edu.sg*; [δ]Current address: KIST Europe, Campus E71, 66123 Saarbruecken, Germany;
*Corresponding author, *E-mail: elelc@nus.edu.sg*

1877-7058 © 2010 Published by Elsevier Ltd. Open access under CC BY-NC-ND license.
doi:10.1016/j.proeng.2010.09.309

110GPa ~ 150GPa [4]. More recently, He et al found the piezoresistive gauge factor of the NW can be as high as 5000 [5], which may yield possibilities of ultrasensitive sensors.

For the first time, we demonstrate a pressure sensor that is integrated with silicon NWs, where the NWs can be precisely fabricated using CMOS processes. Furthermore, we report the electromechanical characteristics for a NW embedded in a 3.5μm thick SiO_2 membrane. It is demonstrated that the sensitivity of the sensor can be enhanced by effective tuning of bias voltage coupled to the substrate. A schematic of the NW based pressure sensor is shown in Fig. 1. A cavity created on the rear side of the device provides access to the controlled pressure. These 200μm wide sensors, can potentially be used as medical devices in cardiac pressure monitoring, intra-cranial pressure monitoring, and may create further impact in medical devices miniaturization.

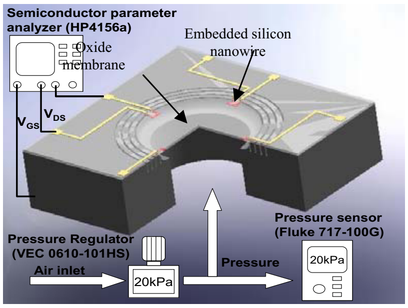

Fig. 1. Schematic drawing of the pressure sensor with embedded silicon nanowires (NWs), showing the test setup for its characterization

2. Fabrication

Pressure sensors with integrated NWs piezoresistive sensors were fabricated using top-down process technology on 200 mm SOI wafer [6]. The process flow was detailed in schematic as illustrated in Fig. 2.

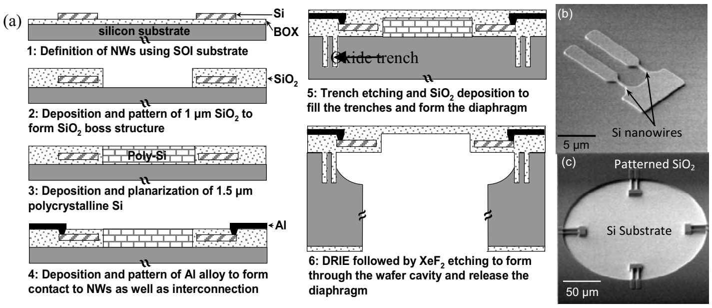

Fig. 2. (a) Fabrication process of the pressure sensor with embedded NWs as electromechanical sensing element (b) a pair of silicon NWs patterned on SiO_2 layer and (c) location of the NWs.

The NWs were defined by lithography first, and followed by photoresist trimming and thermal oxidation, resulting in a cross section of 100 nm x 100 nm with 10μm length. P-type doping was performed with BF_2+ impurity implantation with a dosage of 1 x 10^{13} ion/cm^2, and followed by annealing for activation. Next, an extra layer of SiO_2 was deposited and patterned on the NW to form a bossed structure; the advantage of the bossed structure is to further offset the NW from the neutral plane of the flexible membrane in order to maximize the piezoresistive effect on the NW. At the same time, 18 μm deep and 2 μm wide oxide filled trenches were formed to act as mechanical stiffeners for the SiO_2 membrane. The SiO_2 trenches are also used to confine the isotropic release etching of Si using xenon difluoride (XeF_2) vapor. Subsequently, poly-silicon was deposited and planarized, followed by the metallization of the device. Lastly, a 2.5 μm SiO_2 layer was deposited to form the membrane that would be released eventually.

A two-step process was used to release the pressure membrane. The first step was deep reactive ion etching (DRIE) from the rear side of the wafer, creating an inlet reservoir. Next, Si was isotropic etching using XeF_2 vapor - the advantage of the this method is the reduced chance of misalignment during lithography. Figure 2b and 2c show the SEM images of a pair of NW and the location for each NW.

3. Experimental Section

A standard bulge test was performed to evaluate the piezo-strain relation of the NW embedded in the SiO_2 membrane. A differential pressure was applied to the pressure sensor; meanwhile deflection of the flexible membrane was being observed and recorded under a white light interferometer (WYKO NT3300). The electrical measurement was performed as illustrated in Fig. 1. DC measurement of the current passed through the NW (I_{DS}) was measured by a semiconductor analyzer (HP4156) with varying pressures and different voltage biases (V_{DS}). In addition, the substrate bias (V_G) was coupled to different bias levels to show that enhanced sensitivity can be achieved through effective tuning of the transverse field.

4. Results and Disscussion

The interferometry imaging results were fitted with polynomial functions to remove additional optical effect and plotted as shown on Figure 3 (a). The Young's Modulus of the membrane, E, is given by the equation of deflection of a circular membrane under stress [7]:

$$E = \frac{3 \cdot \Delta P(1-v^2)(a^2-r^2)^2}{16dh^3} \qquad (1)$$

Where ΔP is the difference in pressure, v is the poisson's ratio and a, r, d, h are the radius, radial coordinate of the NW, diameter and thickness of the membrane respectively. It was found that the Young's Modulus of the SiO_2, E = 74 GPa. The specific radial stress of the membrane subjected to different pressure can be found using the equation (2) [8]. An assumption is made that the strain in the membrane is analogous to the strain in the NW, therefore the stress of NW can be extracted and plotted in Fig. 3(b). It is found that the NW's stress is in good accordance with the simulated result (plotted in red) from the FEM model (ANSYS)

$$\sigma_r = \frac{3 \cdot \Delta P}{8h^2}[a^2(1+v) - r^2(3+v)] \qquad (2)$$

Electromechanical measurements of the pressure sensor were performed under room temperature. The results of the NW's resistivity (normalised) with respect to different substrate bias (V_{GS}) were plotted in Fig.4. (a).

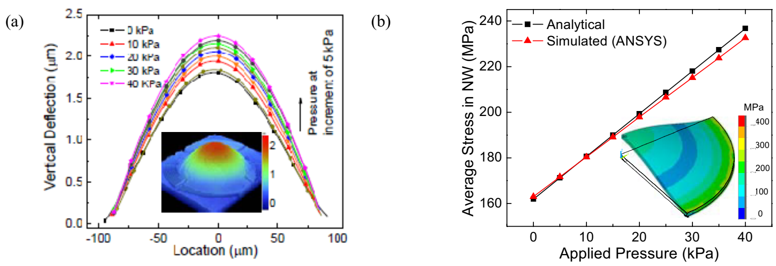

Figure 3. (a) Deflection profile of the membrane as pressure applied from 0 to 40 kPa with 5kPa increment. (b) Average stress within an embedded NW at different applied pressure (analytical vs simulated). (Inset) ANSYS model of the simulated membrane profile.

The substrate bias strongly influenced the electrical conductivity of the NW; i.e. carrier accumulation with negative V_{GS} and carrier depletion at positive V_{GS}. As the pressure was increased further the resistivity with negative V_{GS} showed the highest change in resistance, showing that the sensitivity can be increased when the NW is in enhancement mode, as a result of higher carrier mobility. Fig. 4. (b) shows the device sensitivity extracted from the differentiation of ($\Delta R/R$) as a function of ΔP, with V_{GS} as a parameter. The sensitivity with respect to pressure is enhanced with negative V_{GS}, showing an exponential behaviour.

This results show that outstanding sensitivity can be achieved by optimizing V_{GS}. At V_{GS} = -3V, the measurement results revealed a five-times increase in sensitivity, which corresponds to an ultrasensitive piezoresistive response of $(\Delta R/R)/\Delta P$ of 13 Pa^{-1}. This phenomenon was recently described as the electrically controlled giant piezoresistance in NW [9]. The only downfall of this device is the results were non-linear. The non-linear characteristics of the NW to the V_{GS} would probably require a more complex circuit design incorporated in order to maximize the potential of the device.

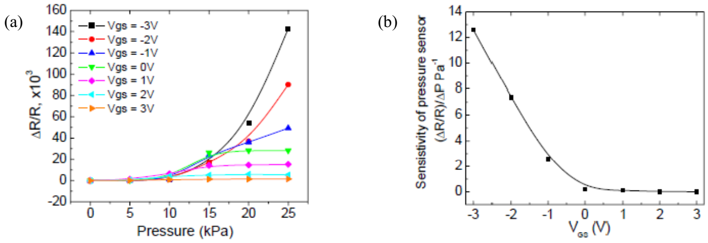

Fig. 4. (a) Resistive response of a NW against varying pressure with V_{DS} = 10V and V_{GS} as parameter. (b) Sensitivity of the NW pressure sensor as a function of V_{GS}.

5. Conclusion

In this work, NW piezoresistive elements were successfully integrated into a pressure sensor. We have also demonstrated that the device can have an enhanced sensitivity with V_{GS} tuning. More work has to be done to fully incorporate the non-linear characteristic of the NW to integrate it into a fully functional device.

Acknowledgements

The authors would like to acknowledge financial support provided by the Science and Engineering Research Council of A*STAR (Agency for Science, Technology and Research), Singapore.

References

[1] Toriyama T, Tanimoto Y, Sugiyama S. Single Crystal Silicon Nano-Wire Piezoresistors for Mechanical Sensors. *Journal Microelectromechanical Systems* 2002; 11, 5, 605-611.

[2] Zhou J, Gu Y, Fei P, Mai W, Gao Y, Yang R et al. Flexible Piezotronic Strain Sensor. *Nano Letters* 2008; 8, 9, 3035-3040.

[3] He R, Yang PD. Giant Piezoresistance Effect in Silicon Nanowires. *Nature Nanotechnology,* 2006; 1, 1, 42-46.

[4] Li Q, Koo S, Edelstein MD, Suehle JS, Richter CA. Electric Field Effects On Young's Molulus of Nanowires. *Nanotechnology*, 2007; 18, (315202), 1-5

[5] He R, Feng XL, Roukes ML, Yang PD. Self-Transducing Silicon Nanowire Electromechanical Systems at Room Temperature. *Nano Letters* 2008; 8, (6), 1756-1761

[6] Agarwal A, Buddharaju K, Lao IK, Singh N, Balasubramaniam N, Kwong DL. Silicon Nanowire Sensor Array Using top-down CMOS Technology. *Sensors and Actuators A*. 2008; 145-146, 207-213

[7] S.P. Timoshenko & S. Woinowsky-Krieger. *Theory of Plates and Shells*, McGraw-Hill, NY, 1959

[8] Park JS, Wilson C, Gianchandani YB. Micromachined Pressure Sensors. *MEMS handbook*, CRC Press, 2002

[9] Neuzil P, Wong CC, Reboud J. Electrically Controlled Giant Piezoresistance in Silicon Nanowires. *Nano letters*, 2010; 10 (4), 1248–1252